ON A RAPID LITHIUM ENRICHMENT AND DEPLETION OF K GIANT STARS

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ABSTRACT

A model scenario has recently been introduced to explain the presence of very strong Li lines in the spectra of some low mass K giant stars (de la Reza et al. 1996). In this scenario *all* ordinary, Li poor, K giants become Li rich during a short time ($\sim 10^5$ yr) when compared to the red giant phase of $5 \cdot 10^7$ yr. In this "Li period", a large part of the stars are associated with an expanding thin circumstellar shell supposedly triggered by an abrupt internal mixing mechanism resulting in a surface new ^{7}Li enrichment. This letter presents near 40 Li rich K giants known up to now. The distribution of these Li rich giants, along with other 41 observed K giants that have shell, but are not Li rich, in a color-color *IRAS* diagram confirms this scenario, indicating, also as a new result, that a rapid Li depletion takes place on a time scale of between $\sim 10^3$ and 10^5 yr. This model explains the problem of the presence of K giants with far infrared excesses presented by Zuckerman et al. (1995). Other present and future tests of this scenario are briefly discussed.

Subject headings: stars: late type–stars: evolution–stars: circumstellar matter–stars: mass loss–infrared:stars

1. Introduction

Since the discovery in the eighties of some K giant stars showing strong lines of Li in their spectra, the main tendency has been to consider these stars as peculiar. This was believed because, following classical first dredge-up theory (Iben 1967), all K giants would have their surface Li depleted due to convective mixing with internal material devoid of this element, or through direct Li destruction by inward transport. In fact, this Li depletion has actually been observed for a large part of the K giants and in several cases, as in the stars with masses lower than $2.5 M_{\odot}$, Li depletions are larger than those indicated by theory, suggesting that an additional mixing mechanism could be present (Gilroy 1989). Some hypotheses have been formulated to try to explain the apparently anomalous presence of Li in the Li rich giants. These are: a) maintenance during the giant phase of a pre-mainsequence large Li abundance. b) engulfing orbiting planets and/or brown dwarfs. c) ^{7}Li production by a nearby nova companion. d) internal production of fresh ^{7}Li.

The maintenance hypothesis is very improbable due first, to mainsequence depletion and second, to the first dredge-up action. Also, the measured isotope ratios of $^{12}C/^{13}C$, which indicate the degree of mixing, appear not to be correlated with strong Li lines; these lines must then be the result of recent Li production (da Silva, de la Reza & Barbuy 1995). In the engulfing as in the maintenance mechanisms, there is no new Li production; Li contained in the planets or in the brown dwarfs (Rebolo et al. 1996) is introduced in the newly formed giant. This mechanism could gain new impetus due to the recent discoveries of extrasolar "51 Peg" type hot planets (Mayor & Queloz 1995). Nevertheless, we know neither if the Li contained in these planets is sufficient to contaminate a star, nor what the proportions of these kinds of planets are when compared to the more distant "cool" planets also recently discovered. These more external planets are not efficient sources for Li in the engulfing process because, due to stellar mass loss, these planets will escape being

swallowed (Sackmann, Boothroyd, & Kraemer 1993). Concerning Novae, even if these objects can eventually produce nearly 15% of the Galactic Li (Hernanz et al. 1996), there is no observational support for the presence of white dwarfs as hot companions to the Li K giants. This is based on IUE observations (de la Reza & da Silva 1995) and on the absence of companions indicated by the lack of radial velocities variations in Li K giants at the 1 km/s level (de Medeiros, Melo, & Mayor 1996). Recently detected variations at the 20 m/s level in the K giant β Ophiucus appear to be due rather to non-radial pulsations (Hatzes & Cochran 1996).

We remain then with the internal production mechanism and the main purpose of this letter consists of presenting observations supporting the idea that Li K giants are not peculiar K giants, but normal giants going through a short Li rich period, presented for the first time in de la Reza, Drake, & da Silva (1996), hereafter called Paper I.

2. The Scenario

In Paper I, a scenario was proposed to explain the existence of Li K giant stars. This model was constructed based on the discovery that almost all Li K giants are optical counterparts of *IRAS* sources indicating the presence of dusty circumstellar shells (CS). Near half of the known Li K giants indicated in this letter were discovered as a subproduct of the search for new T Tauri stars, Pico dos Dias Survey (PDS) made in Brazil (Gregorio-Hetem et al. 1992; Torres et al. 1995; de la Reza et al. 1997). A survey for new Li K giants in *IRAS* color boxes other than that corresponding to T Tauri stars has been initiated by Gregorio-Hetem, Castilho, & Barbuy (1993). First, the presence of a CS region was believed to be, apart from Li, the main difference between Li K and normal K giants. However, Fekel et al. (1996) showed that some K giants could possess CS without showing a strong Li feature. Also, Zuckerman et al. (1995) presented a list of nearly 90 stars, the

large part of which were K giants, with *IRAS* fluxes ratios compatible with the presence of CS regions. No explanation for the presence of large far infrared excesses in these oxygen type giants was found by these last authors. In this paper we report on observations of 27 stars from this list in order to insert them into our scenario.

The main characteristics of the scenario are the following: 1) all normal K giants (at least single field stars with masses between approximately 1.0 to $2.5M_{\odot}$) become Li rich during a short time of $\lesssim 10^5$ yr compared to the red giant phase duration ($5 \cdot 10^7$ yr). 2) An abrupt mixing mechanism producing a rapid surface injection of material with fresh internal ^{7}Be, the only new formed element at this stage via ^{3}He+^{4}He and rapidly transformed to ^{7}Li, produces the formation of a CS of gas and dust. 3) When this sudden mass loss stops, the CS detaches and is ejected into the interstellar medium. The best values for the CS, adjusted to observations (see Paper I), give an expansion velocity of 2 km/s and an equivalent mass loss of $2 - 5 \cdot 10^{-8} M_{\odot}\mathrm{yr}^{-1}$ which is a hundred times the normal mass loss of ordinary K giants. The complete ejection of the CS up to the stage when it is no longer detectable lasts at least $8 \cdot 10^4$ yr. 4) The fresh ^{7}Li that has not been ejected into the interstellar medium remains in the stars' photospheres. This surface Li will be depleted later in a time less or equal to the total CS ejection time, depending on the stellar parameters. This depletion mechanism is probably related inversely to the additional mixing mechanism introduced to produce the Li enrichment.

3. Observations

The results presented in this paper were obtained from spectroscopic observations using the following telescopes: 1) The CTIO 4.0 m in Cerro Tololo - Chile with an echelle spectrograph with 0.08Å/pixel (April - May, 1996); 2) The 3.5 m of the Calar Alto Observatory (Almería, Spain) with the TWIN spectrograph with 0.88Å/pixel (July,

1996); and 3) The 2.5 m Isaac Newton (La Palma, Spain) with the IDS spectrograph with 0.85Å/pixel (November, 1996). The first main program stars consisted of a group of faint Li K and Li poor K giants discovered in the PDS. These PDS observations were restricted to coude spectra of a small spectral interval between H_α and the Li I resonance line. The main interest in obtaining echelle spectra was to perform a detailed analysis in order to derive the main stellar parameters. The second program stars consisted of relatively bright K giants belonging to the list of Zuckerman et al. (1995). Bearing in mind that these stars have *IRAS* colors indicating the presence of CS regions, these objects were potential candidates for new Li K giants. The observed results presented in this letter are limited to the presence, or lack thereof, of strong Li lines. A next paper will be devoted to the determinations of the masses and metallicities of these objects.

4. Discussion of the Results and Tests of the Model

The most complete list of observed Li K giants known up to now is presented in Table 1, where K giants are considered between the included spectral types limits of G8 and M0. In this Table numbers with an asterisk indicate the Li K giants which are represented in Fig. 1 with their respective labels. From the observational point of view, we considered as Li K giant stars those presenting the resonance Li I line at 6708Å with intensities comparable to or higher than the neighbor Ca I at 6718Å. When the Li abundance is known, "Li K giants" are stars with Li abundances larger than $\log\epsilon(\mathrm{Li}) = 1.2$ (where $\log\epsilon(\mathrm{H}) = 12.00$). K giants presenting no strong Li lines and having far infrared excesses belong to the list of Zuckerman et al. (1995) (with HD numbers) and to the PDS list (with *IRAS* numbers). Apart from the bright and already known Li K giants discovered by several authors resulting in 21 objects, we have added 20 new Li K giants discovered in the PDS (Gregorio-Hetem et al. 1992; de la Reza et al. 1997) at fainter visual magnitudes. These groups, bright (m_V

of $3^m - 8^m$) and faint ($9^m - 14^m$), are located in different places in a color-color diagram with *IRAS* fluxes at 12, 25 and 60 μm (see Fig. 1). The explanation of this separation in apparent magnitudes appears naturally in the model of Paper I. In that paper is considered the existence of three regions in the diagram of $[60 - 25]$ vs $[25 - 12]$ labeled I, II and III (see Fig. 1). In region I are the bright, commonly called, normal K giants with *IRAS* colors of photospheric origin showing the absence of CS regions. It is in this region that almost all the Li poor giants are found. Region II corresponds to the color box used in the PDS to discover new T Tauri stars. It is in this region that the new faint recently discovered Li K giants are placed . In region III are found all the previously known visual bright Li K giants. Some of the curves resulting from the model of Paper I are presented in Fig. 2. They represent the evolutionary paths of the ejections of the CS regions. Beginning in I, they go to II and then III before returning to I. This loop takes at least $8 \cdot 10^4$ yr. The stars remain for a long time in region I during the red giant phase.

When stars become ^{7}Li enriched in a rapid episode, a CS is formed. When the mass loss (and the associated Li enrichment) stop, the CS detaches from the star ejecting its matter into the interstellar medium. In this way ^{7}Li surface enrichment and subsequent depletion are time adjusted with the expansion of the CS. Any expansion time can then be used to measure the ^{7}Li depletion during the loops shown in Fig. 2.

There are no observed stars between regions I and II due to the very short corresponding evolutionary times (of the order of hundreds of years). In region II only faint giants are observed. Even if the corresponding times are longer in this part of the diagram (more than one thousand years), they are too short to observe objects in part II among the nearby stars. We must then survey a larger region consisting of more distant and faint giants. In region III, the crossing times are nearly ten thousand years, and these longer times give the possibility of observing some Li K giants among the bright and nearby stars.

In Paper I it was mentioned that Li K giants contain a large majority of CS stars. This gives us the idea that normally Li poor K giants have no CS regions and that the Li depletion times were of the order of 80 000 yr, or somewhat larger. The possibility that some K giants having a CS region without high Li could exist, was pointed out by Fekel et al. (1996). They suggested that Li depletion times could be smaller than 10^5 yr, or even that CS could be formed without Li enrichment. The most important result of this letter is to show that the first conclusion is the most probable. This can be seen very clearly in Figs. 1 and 2. There is a group formed of Li K giants only in the lower part of region II, having the largest $[25 - 12]$ and lowest $[60 - 25]$ values. Those stars would be the most recently formed Li K giants! During the PDS we found some faint K giants without high Li, however less numerous than the Li K giants. Nevertheless, these Li poor CS K giants are all in the upper part of region II. These stars would then be the first Li depleted giants. All but one of the giants belonging to the list of Zuckerman et al. (1995) are in the left part of the diagram (region III and in the intersection of III and I).

In observations of 27 stars of the Zuckerman et al. list, we didn't discover any new Li K giants, only Li poor K giants. These stars are then surface depleted Li K giants. After all, the time scales over which depletion can occur are longer in region III than in region II. The only star of the Zuckerman et al. (1995) list belonging to the lower part of region II was HD 19745 and this star had already been discovered to be very Li rich in the PDS (Gregorio-Hetem et al. 1992, see also de la Reza & da Silva 1995). In conclusion, with the exception of a homogeneous group of pure "young" Li rich K giants in the lower part of region II, the Li rich and Li poor giants are mixed indicating that different Li depletion times occur. The observed positions in Fig. 2 give depletion times between $\sim 10^3$ and 10^5 yr. Some Li K giants, such as HD 39853 or HD 787, are placed in region I showing no CS. Those stars are considered to have lost their CS but have not yet depleted their Li. The Li K giant HD 95799 detected by Luck (1994) is the only Li K which is not an *IRAS*

source. The explanation is that this star is also in region I, like HD 39853 and HD 787, but is not detected by *IRAS* because it is more distant than these last ones. In fact, the visual magnitude of HD 95799 is $m_V = 8.01$, whereas those of HD 39853 and HD 787 are respectively 5.66 and 5.25.

Li enrichment and depletion in K giants appears then to be the explanation to the problem posed by Zuckerman et al. (1995) with respect to the existence of oxygen giants with strong far infrared excesses. Is stellar mass the factor which determines a shorter or longer depletion time? Determinations of the main stellar parameters of these CS stars, with and without high Li, could give an answer to this question. Other important parameters, such as a strong differential rotation (Fekel et al. 1996) or metallicity could, however, have a significant part in this rapid enrichment-depletion process.

Some questions have no answer yet. Can stars become Li rich several times during the giant phase? This, in principle, depends on the quantity of available ^{3}He, which acts as a fuel for the production and enrichment of ^{7}Be, subsequently transformed into ^{7}Li. Direct observational evidence of this could be shown by the eventual detection of double detached CS. Another question refers to the internal nature of these stars. Are they first ascent red giant or clump giants? We do not propose an answer to this yet, due to uncertainties related to the positions of these stars in the HR diagram. As can be seen in Paper I, these stars are somewhat grouped in the HR diagram. Future accurate determinations of the stellar parameters will elucidate this question. Other considerations are important; this "Li phenomenon" has been observed only for single field giants spread over all Galactic latitudes. No clear identification of a Li K giant belonging to a cluster has yet been made. This will be important to determine the "Li age" for these stars. From the theoretical point of view, considerable advance has been made on the stellar internal ^{7}Li production and surface enrichment in low mass K giants ($1 - 2.5 M_\odot$) by means of an internal circulation

mechanism (Sackmann & Boothroyd 1997). This one relates the base of the convective layer to a hot region producing the ^{7}Be. Larger Li abundances can be obtained depending upon certain values of the circulation mechanism, as the mixing speed, the depth of mixing, the star's metallicity, and possibly the star's mass. For example, large Li abundances as $\log\epsilon(^7\mathrm{Li}) = 4.2$ were obtained for a $1M_\odot$ star of metallicity $Z = 0.0001$ with a rapid mixing to greater depths.

Perhaps one of the most interesting points of the scenario of Paper I is that it can be tested by several means. One has already been made by Fekel et al. (1996) by means of the determination of the real nature of the star HDE 233517. This object was considered by Skinner et al. (1995) and Miroshnichenko, Bergner & Kuratov (1996) to be a nearby K dwarf star of the "Vega" or "β Pictoris" type. Fekel at al. (1996) showed that this star is in reality a distant K giant with a large mass loss (object number 15 in Fig. 1). According to its position in the color-color diagram this star should be probably Li rich and, according to its corresponding mass loss and age of its shell, its CS should be of a specific size. Both points have been confirmed by observations (Fekel et al. 1996). Other general tests can be made such as detection of the sizes and velocities of the CS, presence of CS detachment and/or double shells. Also, observations of the presence of ^{9}Be, ^{10,11}B and ^{6}Li will give an insight into the rate of the ^{7}Li enrichment process (Sackmann & Boothroyd 1997). A Non LTE Li abundance determination of several prototype stars in different regions of the color-color diagram is in progress. These determinations will help us to quantify their Galactic Li enrichment contribution.

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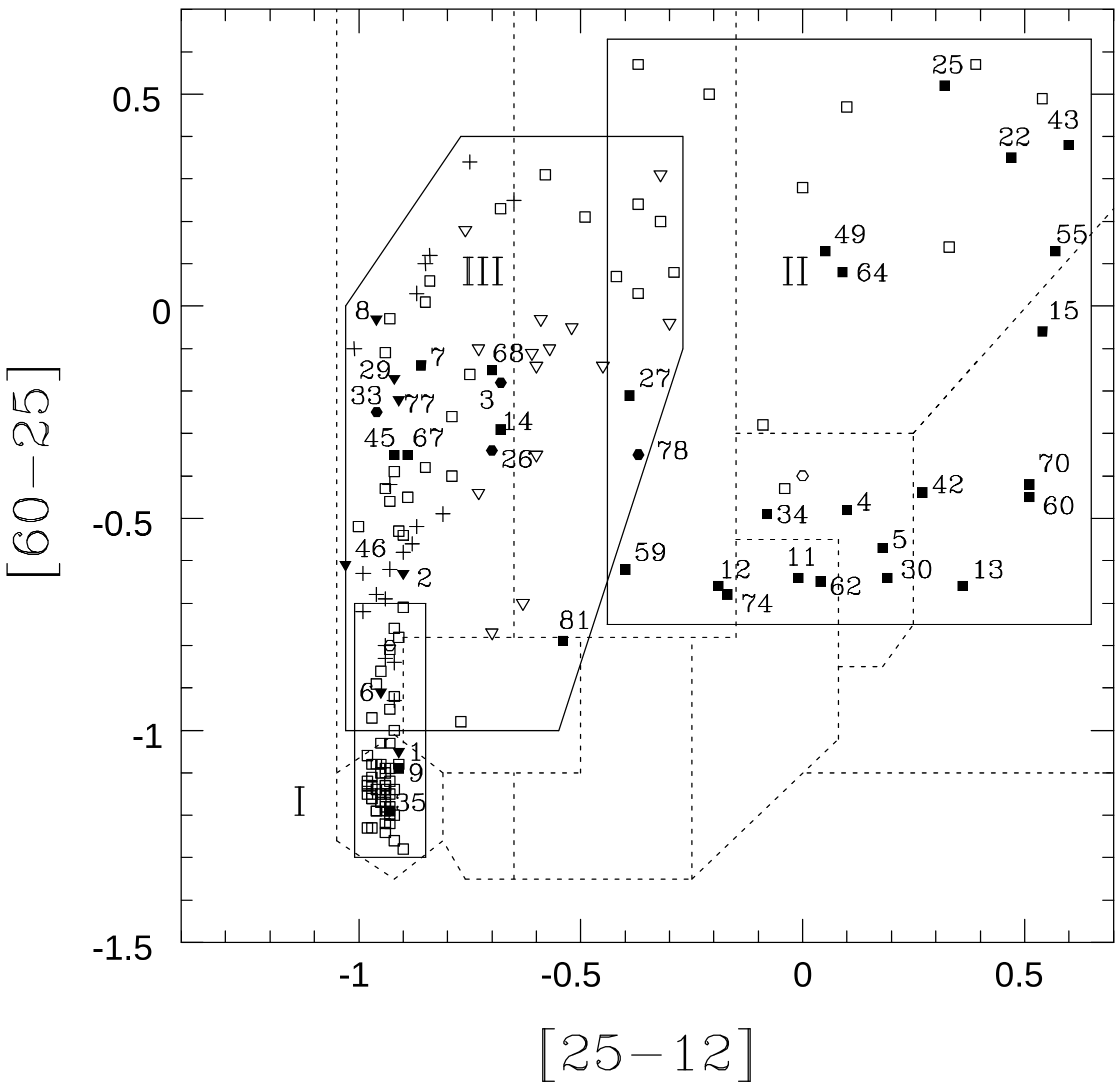
Fig. 1.— Distribution of *IRAS* sources corresponding to K giants contained in three regions labeled I, II, and III marked by solid lines. The regions marked by broken lines are those defined by van der Veen & Habing (1988). Labeled filled symbols correspond to *Li strong K giants*: squares (three fluxes are of good quality), triangles (one flux is only an upper limit) and hexagons (two fluxes are only upper limits). Corresponding open symbols represent *Li weak K giants*. Crosses represent K giant stars of the Zuckerman et al. (1995) list with CS regions and which have not yet been observed in the spectral Li region.

Table 1: List of K giants observed in the Lithium spectral region.

1*	HD 787	29*	HD 112127	57	HD 162298
2*	HD 9746	30*	IRAS 13313–5838	58	IRAS 17576–1845
3*	CPD-55395	31	HD 118344	59*	IRAS 17578–1700
4*	HD 19745	32	HD 119853	60*	IRAS 17582–2619
5*	IRAS 03520–3857	33*	HD 120602	61	IRAS 17590–2412
6*	HD 30238	34*	PDS 68	62*	IRAS 17596–3952
7*	HD 30834	35*	HD 121710	63	HD 164712
8*	HD 31993	36	HD 125618	64*	IRAS 18334–0631
9*	HD 39853	37	HD 128309	65	IRAS 18397–0400
10	IRAS 06365+0223	38	HD 129955	66	IRAS 18559+0140
11*	IRAS 07227–1320	39	HD 131530	67*	HD 176588
12*	IRAS 07456–4722	40	IRAS 14198–6115	68*	IRAS 19012–0742
13*	IRAS 07577–2806	41	IRAS 14257–6023	69	HD 177366
14*	HD 65750	42*	IRAS 16086–5255	70*	IRAS 19083+0119
15*	HDE 233517	43*	IRAS 16128–5109	71	HD 181154
16	HD 76066	44	HD 146834	72	IRAS 19210+1715
17	HD 82227	45*	HD 146850	73	HD 183202
18	HD 82421	46*	HD 148293	74*	PDS 100
19	IRAS 09553–5621	47	IRAS 16227–4839	75	HD 187114
20	HD 92253	48	IRAS 16252–5440	76	HD 190299
21	HD 95799	49*	IRAS 16514–4625	77*	HD 194317
22*	IRAS 11044–6127	50	HD 153135	78*	HD 203251
23	HD 96996	51	HD 156061	79	HD 204540
24	HD 97472	52	HD 156115	80	HD 218527
25*	IRAS 12236–6302	53	IRAS 17102–3813	81*	HD 219025
26*	HD 108471	54	IRAS 17120–4106	82	HD 221776
27*	IRAS 12327–6523	55*	IRAS 17211–3458		
28	HD 111830	56	IRAS 17442–2441		

Fig. 2.— The same points as in Fig. 1 are presented here together with evolution curves of CS (see Paper I). The four curves calculated for CS expansion velocity of 2 km/s, stars temperatures and radii equal to 4000 K and $20R_{\odot}$ respectively, correspond to mass losses between 10^{-9} and $10^{-6}M_{\odot}$/yr. The blackbody curve (straight dashed line) and time steps are also indicated.



[60−25]
[25−12]
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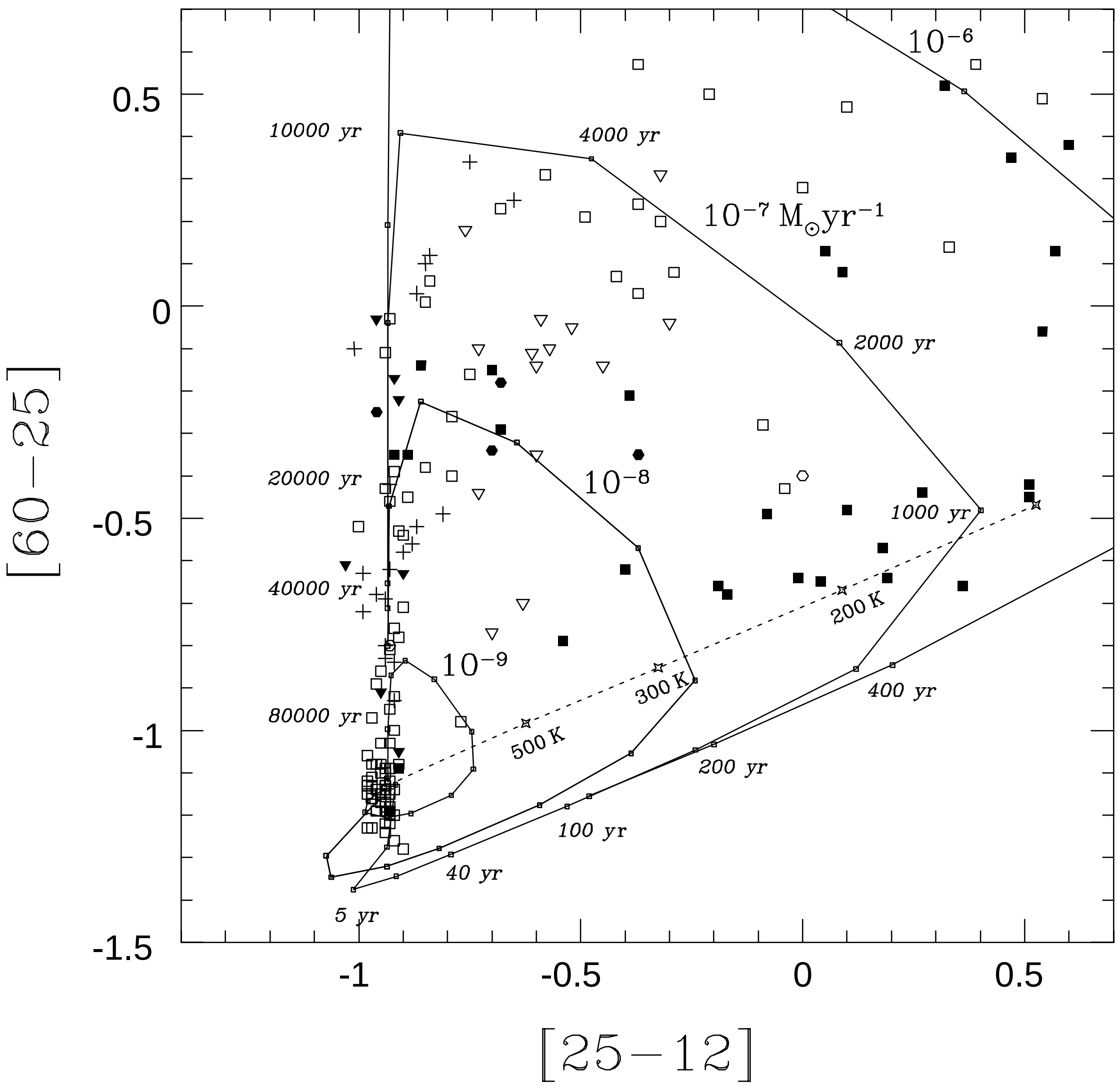

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100 yr
40 yr
5 yr
20000 yr
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80000 yr
200 K
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[60−25]
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